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Published in:
Procedia Environmental Sciences

DOI:
10.1016/j.proenv.2011.03.003

Publication date:
2011

Available online at www.sciencedirect.com
ScienceDirect
Procedia Environmental Sciences 4 (2011) 17–24
Procedia Environmental Sciences

Urban Environmental Pollution 2010

Large eddy simulation of the aerodynamic effects of trees on pollutant concentrations in street canyons

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Received date September 30, 2010; revised date January 30, 2011; accepted date January 30, 2011

Abstract

This paper presents numerical simulations of the aerodynamic effects of trees on the flow field and dispersion of traffic-originated pollutants in an urban street canyon of W/H = 1 with a perpendicular approach flow. Large Eddy Simulation (LES) is employed for the investigation and is validated against wind tunnel (WT) experiment. Comparisons is made between an empty street canyon and one containing avenue-like tree planting of pore volume, P_{vol} = 96%. In the presence of trees, both measurements and simulations show considerably larger pollutant concentrations near the leeward wall and slightly lower concentrations near the windward wall in comparison to the tree-free case.

Keywords: Street canyons; Trees; Air pollution.; CFD; LES.

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1. Introduction

Air quality in urban areas is of great importance owing to the many implications on human health and environmental integrity. Research is underway to understand air flow and pollutant dispersion processes in built up areas in order to develop numerical models able to assist policy-makers and urban planners. The aims are twofold: first, there is the necessity to ensure that air quality is not compromised by unreasonable urban and traffic planning as discussed by Hester and Harrison [1] and second, to ensure that the numerical tools employed are reliable and effective [2].

Numerous experimental and numerical investigations on urban air quality problems in 'empty' street canyons have been performed and the flow and transport mechanism are well understood (see reviews by [3,4]). All these studies deal with a prevailing atmospheric wind directed perpendicular to the street canyon axis, since this wind regime is determined to be the most critical for pollutant accumulation in street canyons. This brings to question to what extent tree planting in street canyons would affect the pollutant dispersion and exchange processes with the above-roof air flow, as tree crowns occupy a considerable fraction of street canyons separating the lower street level

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doi:10.1016/j.proenv.2011.03.003

from the above.

Gromke and Ruck [5] experimentally examined the impact of trees on the air flow and pollutant distribution in boundary-layer wind tunnel (WT) studies. They found that entrainment conditions and, thus, air exchange mechanisms were altered by the trees, resulting in lower flow rates and an overall increase in pollutant concentration within the canyon as compared to the corresponding tree-less configuration. Gromke et al. [6] then complemented the investigation with a Computational Fluid Dynamics (CFD) study comparing the WT experimental results with numerical simulations employing the steady Reynolds-averaged Navier-Stokes (RANS) turbulence models, namely the standard k-ε and Reynolds Stress Model (RSM), using the commercial code FLUENT. They concluded that RSM performed better than k-ε in predicting the flow fields, although both generally under-predicted the flow velocity and consequently the volume fluxes of circulating air masses inside the street canyons were underestimated which resulted in larger pollutant concentration as compared to experimental observations.

RANS assumes that non-convective transport in a turbulent flow is governed by stochastic three-dimensional turbulence possessing a broad-band spectrum with no distinct frequencies and, therefore, models all the eddy length scales without distinction. This method has obvious weaknesses and poses serious uncertainties in flows for which large-scale organized structures dominate. In addition, RANS models often assume gradient transport, which may not be the case for pollutant exchange within street canyons. Large Eddy Simulation (LES), although computationally more expensive, has an advantage over RANS in that it explicitly resolves the majority of the energy carrying eddies and the internally or externally induced periodicity involved, and only the universally small eddies are modeled. LES' ability to reproduce the unsteady and intermittent fluctuations of flow fields and, thus, capture the transient mixing process is what makes it numerically superior to conventional RANS, particularly for studies dealing with complex geometries and pollutant dispersion problems.

With this in mind, the present work aims at replicating the aforementioned investigations on the aerodynamic effects of trees on the traffic-induced air pollution concentration in urban street canyons, employing LES to test the performance over these cases. Flow and concentration levels are analyzed in terms of comparisons between an empty street canyon and one containing avenue-like tree planting. The role played by the transient mixing processes is essential in determining final concentrations and is resolved by LES. In addition to the mean-flow solutions, the three-dimensional distribution and time-evolution of the concentration field at the street canyon's façade walls are presented, in line with the recommendations for the need to resolve the unsteady and intermittent fluctuations as discussed by [7]. This also demonstrates how numerical simulations may be used to obtain flow and concentration fields in detailed locations at various time instances in cases where experimental or field measurement points are limited. CFD validation is an essential step towards the standardization of more advanced CFD modeling procedures to be used in real urban scenarios.

2. Numerical Modeling

2.1. Experimental Setup

The present numerical study uses concentration data obtained from experiments and accessible to the scientific community online at www.codasc.de. Measurements at a model scale street canyon were performed in an atmospheric boundary layer WT. In the test section, a boundary layer flow with mean velocity profile $u(z)$ with exponent $\alpha = 0.30$ and turbulence intensity profile I_u with exponent $\alpha_I = 0.36$, according to the power law were reproduced:

$$\frac{u(z)}{u(z_{ref})} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \text{ and } \frac{I_u(z)}{I_u(z_{ref})} = \left(\frac{z}{z_{ref}}\right)^{-\alpha_I} \quad (1)$$

A free stream velocity of $u(z_{ref}=H) = 4.70\ m\ s^{-1}$ with H being the building height was realized. In the test section, a 1:150 scaled model of an isolated street canyon of length $L = 180\ m$ and street width $W = 18\ m$ with two flanking buildings of height $H = 18\ m$ and width $B = 18\ m$ was mounted perpendicular to the approach flow. Integrated in the model street, four Sulfur hexafluoride (SF_6) tracer gas emitting line sources were used for simulating the release of traffic exhausts with emission rate $Q = 10gs^{-1}$. Mean concentrations and vertical velocities were normalized according to

$$c^{+} = \frac{cu_{H}H}{Q/l} \text{ and } w^{+} = \frac{w}{u_{H}} \quad (2)$$

with c measured concentration, w vertical velocity, u_H flow velocity at height H in the undisturbed approaching flow and Q/l tracer gas source strength per unit length. The tree crowns were modeled as porous media, with a pore volume, $P_{vol} = 96\%$ corresponding to a pressure loss coefficient, $\lambda = 200\ m^{-1}$ obtained from measurements in forced convection conditions. The readers are referred to work of Gromke and Ruck [5] for more comprehensive details of the experimental setup and corresponding measurements.

2.2. Fluent Setup

2.2.1. Computational Domain and Boundary Conditions.

Simulations were performed by means of the CFD code FLUENT [8] employing the LES viscous model. The computational domain and boundary conditions for the street canyon are summarized in Figure 1.

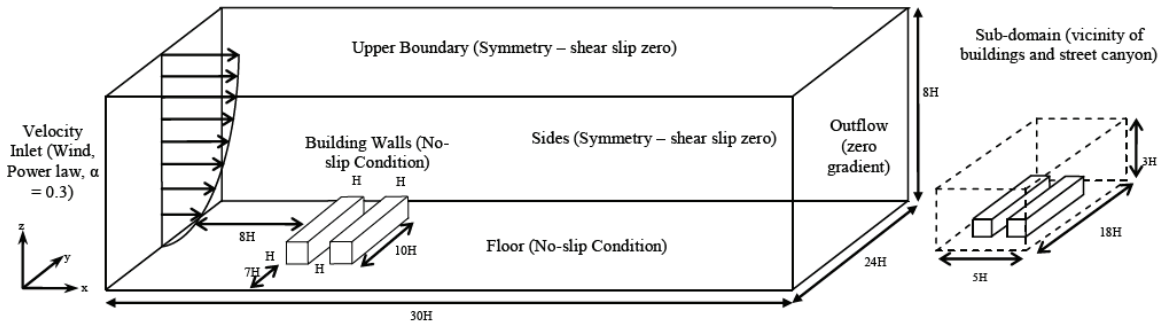

Figure 1. Computational domain including street canyon sub-domain and boundary conditions.

The computational domain was discretized using hexahedral elements incorporating recommendations by Salim et al. [9] with approximately half of the total cells placed in the sub-domain defining the vicinity of the buildings and street canyon so as to impose a finer mesh resolution in the region of interest, where large gradients in the solution variables exist. From a grid independence test, a mesh with 1.1 million cells was chosen with a minimum grid spacing of 0.08H in the x, y and z directions. In order to replicate the WT experiment, numerically described User-Defined Functions (UDFs) were implemented for the inlet boundary condition profiles for the velocity, turbulence kinetic energy and dissipation rate. Figure 2 demonstrates the simulated UDF profiles, which are similar to the WT experiment inlet conditions (equation 1).

2.2.2. Flow Simulation

LES is one of the mathematical tools for computing turbulence in CFD, and is employed for the present study instead of the conventional RANS models used in previous studies, so as to determine if improvements can be obtained. In LES, the large eddies are solved directly and only the influences of the small-scale eddies on the large-scale eddies are modeled. A spatial filtering operation is used to separate the large-scale and small-scale eddies of the flow, resulting in the filtered continuity and momentum equations of the incompressible Navier-Stokes as follows:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \, and \, \frac{\partial \overline{u_i}}{\partial t} + \frac{\overline{u_j}(\partial \overline{u_i})}{\partial x_i} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \upsilon \frac{\partial^2 \overline{u_i}}{\partial x_j{}^2} - \frac{\partial \tau_{ij}}{\partial x_j} \quad (3)$$

u_i and p_i are the filtered velocity and pressure in the x_i-direction, ρ is the density, υ is the viscosity and τ_{ij} are the subgrid-scale (SGS) stresses, The dynamic Smagorinsky-Lily SGS model together with bounded central differencing discretization scheme for momentum and second order upwind for species and energy transport equations were selected. PRESTO and SIMPLEC were used for pressure and pressure-velocity coupling, respectively. The simulation was initially ran for 33 flow-through times $T = L/U_b$ with L being the streamwise length of the domain and U_b the bulk velocity, corresponding to 1000 large-eddy turnover times $T_b = H/U_b$. A check was performed with 50 flow-through times and it was observed that both symmetry and mean flow property magnitudes did not improve over the 33 flow-through times, implying that statistically steady state was already achieved. The flow statistics were then reset and allowed to run for a further 33 flow-through times enabling a large sampling time to ensure that the final time-averaged results were independent of the initial conditions. A temporal resolution ($\Delta t/T_b$ with Δt the time-step size) sensitivity study was also performed and a resolution of *1/8* was decided upon, taking into account a compromise between accuracy and computational cost.

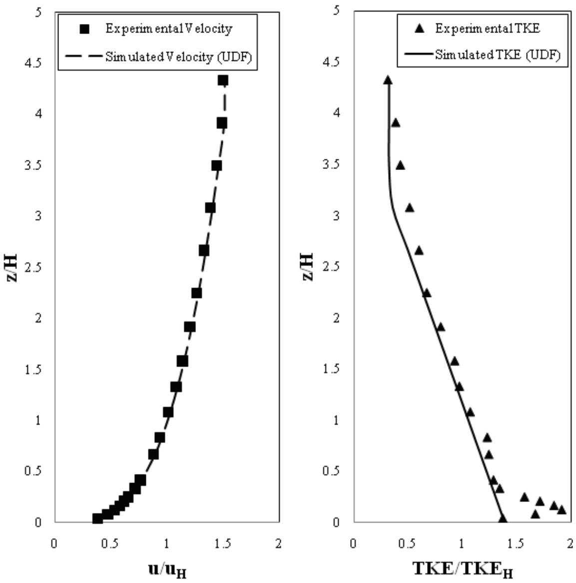

Figure 2. Velocity and TKE profiles for the inlet boundary condition showing comparison between the simulated profile created using User Defined Functions (UDF) and WT experimental profiles.

The advection diffusion (AD) method was used for the dispersion of the pollutant.. In turbulent flows, FLUENT computes the mass diffusion as follows:

$$J = -\left(\rho D + \frac{\mu_t}{Sc_t}\right)\nabla Y \quad (4)$$

where D is the molecular diffusion coefficient of the pollutant in the mixture, μ_t is the turbulent viscosity, Y is the mass fraction of the pollutant, ρ is the mixture density and Sc_t is the turbulent Schmidt number. The tree crowns are modeled as porous media and assigned the pressure loss coefficient λ deduced from the WT experiment. In essence, the porous media model in FLUENT contributes a momentum sink to the standard fluid flow equations incorporating an empirically determined flow resistance in the region of the computational domain defined as the porous zone. This additional source term is described as:

$$S_i = -\left(\sum_{j=1}^{3} D_{ij}\mu \upsilon_j + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho|\upsilon|\upsilon_j\right) \quad (5)$$

where S_i is the source term of the ith momentum equation, $|v|$ is the magnitude of the velocity and D and C are prescribed matrices. Both the line source and tree crown were simulated by ear-marking section of the volume in the geometry and defining them as separate fluid zones at the required positions with their respective properties. For further details on the numerical schemes, the reader is referred to the documentation provided by FLUENT [8].The position of the trees and line sources for both the experimental setup and in the computational domain are presented in Figure 3.

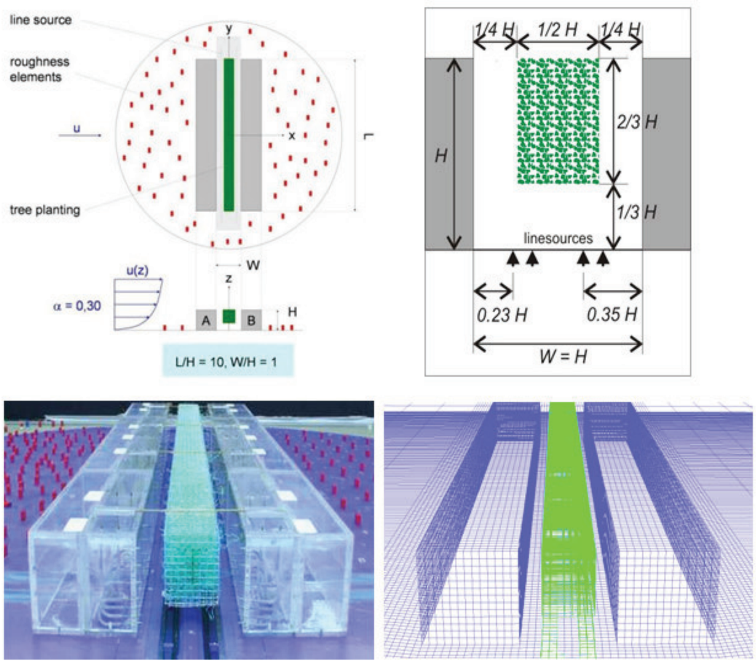

Figure 3. Tree model and line source positions in the WT experiment and computational domain (©CODASC, www.codasc.de)

3. Results and Discussion

The LES and WT time-averaged (mean) concentration results are presented along the façades of the leeward (Wall A) and windward (Wall B) street canyon walls for both the tree-free and tree-lined case, demonstrating the relative performance of LES in comparison to the WT measurements. Comparing the two cases as presented in Figure 4, it can be seen that the introduction of the tree planting adversely affects the flow field resulting in overall larger. This could be explained by the fact that the tree crowns act as a momentum sink reducing the air-circulation within the canyon and obstructing the air-exchange with the above-roof flow. As a consequence, less pollutant is transported out of the canyon due to this reduced ventilation. This is much more evident at the leeward wall (Wall A) where larger concentrations are found in the tree-lined case when compared to the tree-free canyon.

Figure 5 presenting the LES numerical results of the normalized vertical velocity w^+ and corresponding concentration contours c^+ of the tree-free and tree-lined cases along the mid-plane of the street canyon (i.e. y/H = 0 in the x-direction) helps demonstrate this. It can be observed that the positive velocity (i.e. outgoing air mass at Wall A) is reduced in both strength and size in the presence of trees and as a result larger pollutants are found in that region.

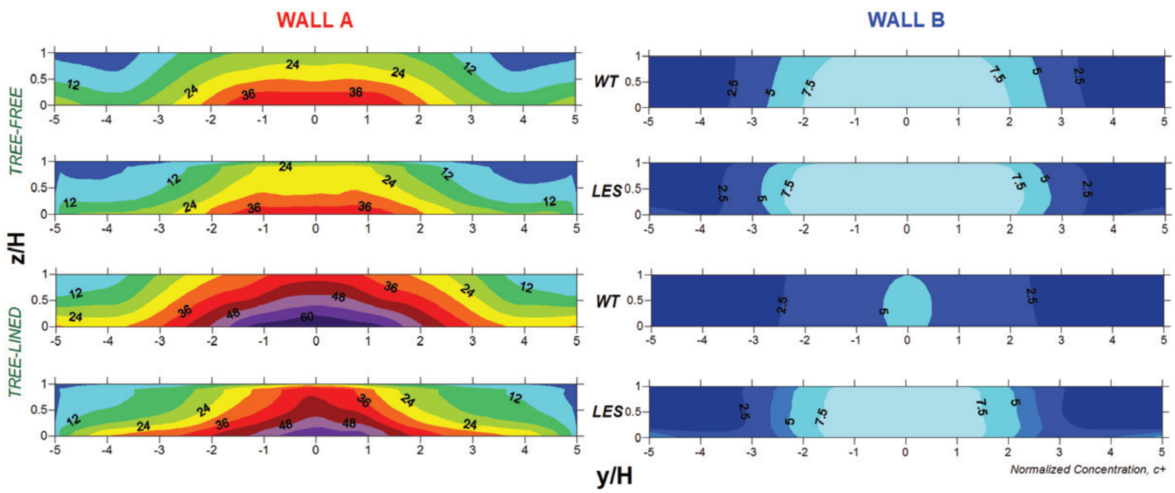

Figure 4. Mean normalized concentrations c^+ at the walls of the tree-free and tree-lined street canyons for wind-tunnel data and numerical results.

Numerical results obtained from LES show good agreement with WT measurements for both the tree-free and tree-lined case, particularly at the leeward wall (Wall A) but slightly over-predict the concentration at the windward wall (Wall B) for the tree-lined case. This is an improvement over previous results obtained by Gromke et al. [6] employing RANS but the computational cost is nearly twenty times larger (for example, k-ε took 12hrs and RSM took 36hrs whereas LES took 30 continuous days on an Intel Xeon® workstation running on 4 parallel processors).

Overall, LES provides detailed information and statistics of the scalar properties that vary both in time and space (including the streamwise direction as shown in Figure 5) in contrast to WT experiments which recorded the mean data (over a sampling period) and only presented concentration results at limited measuring points (i.e. 49 taps at each wall) on the walls and not for the streamwise direction. Similarly, no flow field information (e.g. vertical velocity within the canyon) is available in the WT database. That is why Figure 5 only presented results obtained from LES computation since no data was available from the experiment.

Figure 6 shows an example of the intermittent and unsteady fluctuations of the pollutant concentration obtained by LES (again, WT only provided the mean data), with peak values several times the mean and demonstrates the need to resolve them as discussed by Louka et al. [7]. The transient mixing as a result of the reproduction of unsteadiness within the street canyon is resolved by LES providing better predictions than steady RANS obtained in the previous study of Gromke et al. [6].

Similarly, the horizontal diffusion of concentration is better predicted by LES. For further discussion on the relative numerical performances between LES and RANS, interested readers are referred to a more comprehensive investigation by the authors [10].

4. Conclusions

The presence of trees in street canyons adversely alters the airflow and, thus, the dispersion of pollutant. It is observed that larger concentrations are obtained in the tree-lined case in comparison to the tree-free canyon particularly at the leeward wall due to the reduction of air ventilation by the trees acting as obstacles to the flow. The numerical results obtained by LES are reliable demonstrating the ability of CFD simulations to be employed as a complement to experiments and in some cases has an advantage over WT in that they can provide more details overcoming some of the limitations of experiments. This encourages the use of CFD as a tool to policy makers and urban planners.

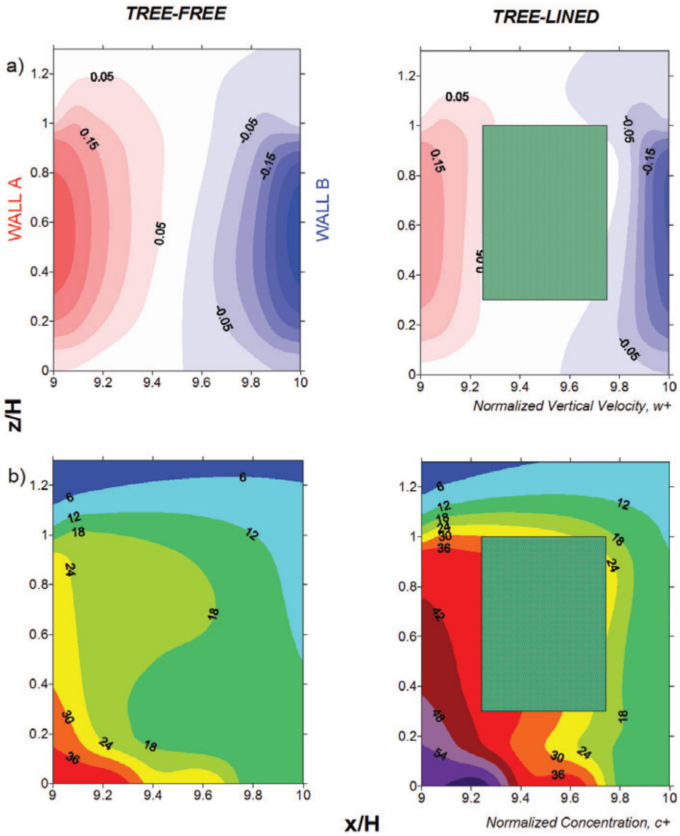

Figure 5. (a) Mean normalized velocity w^+ and corresponding (b) mean normalized concentration c^+ for the tree-free and tree-lined cases obtained from LES.

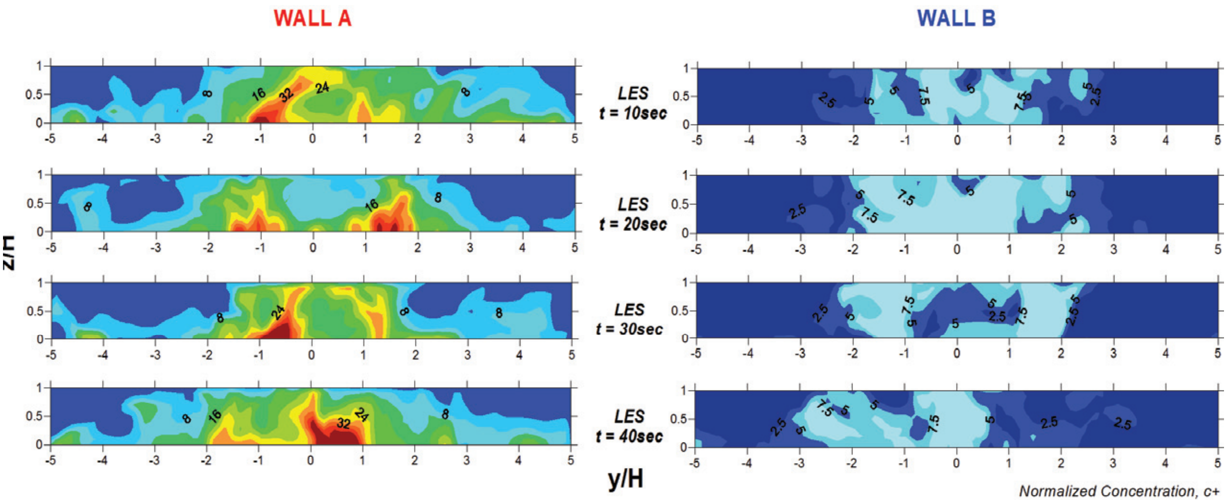

Figure 6. Instantaneous and mean normal concentrations c^+ demonstrating the time-evolution of the pollutant concentration as obtained by LES.

Acknowledgement

The financial supports from the Environmental Issues Award by the Institute of Mechanical Engineers (IMechE) and from the BESTS fund courtesy of the Graduate School, University of Nottingham are gratefully acknowledged.

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